Dark Photons in the Dalitz-like decay of a scalar

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DP: what do we know

New Physics: …., Dark matter/ Dark photons, …. Monophotons

Search through: Cosmological observations or lab's experiments

Accelerator exp's: - CERN SPS

$$e^- Z \to e^- Z \bar{\gamma} \to e^- Z \; e^+ e^-$$

$$10^{-5} < \varepsilon_{\gamma-\bar{\gamma}} < 10^{-3}$$

NA64

S. Gninenko PRD 89 (2014) 075008

- SINDRUM, PSI

$$\pi^- p \to \pi^0 n \to \gamma\bar{\gamma} n \to \gamma e^+ e^- n$$

$$\varepsilon_{\gamma-\bar{\gamma}} > 10^{-3}$$

S. Gninenko PRD 87 (2013) 035030

Colliders @ high energies (LHC/…/FCC…)

$$S \to \gamma\bar{\gamma} \to \gamma \; \bar{\nu}\nu, \;\; S = H, \ldots$$

$$\varepsilon_{\gamma-\bar{\gamma}} < 3 \cdot 10^{-2} \qquad \boldsymbol{O}_{SM} O_{IR} \sim \varepsilon \bar{\boldsymbol{q}} \gamma_\mu q S B_\mu M^{-1}$$

G.K. arXiv:1604.04599(2016)

In the absence of an **explicit sector that breaks gauge invariance**, the interactions of SM gauge bosons with fermions are **approximately conformal** down to QCD scale $\Lambda_{QCD} \sim O(1 GeV)$.

- Could we see something else – not in terms of SM?
- Should one expect new stuff? Great!
- **Scale invariant hidden world?**

✓ The question of **triggering gauge symmetry breaking** in the SM is tied to the dynamical breaking of scale invariance.

Hidden world

At high enough energies $Q \sim O(M)$ (**UV**, Cosmology)

the nearly conformal (matter) sector couples in the UV to the HIDDEN world through the exchange of heavy state(s), the messenger(s)

Mediators in terms of ATLAS – CMS LHC Forum, arxiv:1507.00966

Stage I

$$\begin{bmatrix} Nearly \\ conformal \end{bmatrix} \underset{messenger(s)}{\overset{heavy}{\leftrightarrow}} \begin{bmatrix} Hidden \\ world \end{bmatrix}$$

$$Below\ UV\ \ M\ : \frac{1}{M^{d-4}} O_{SM} \frac{1}{M^{d_{UV}}} O_{UV}$$

No masses allowed

All masses can be generated dynamically in **IR.**

Conformal symmetry is spont. broken – low energy eff. theory contains a dilaton field

$$x_\mu \to x'_\mu = e^{-\lambda} x_\mu, \; \boldsymbol{S} = \bar{\sigma}, \; \bar{\sigma}(x) \to \bar{\sigma}'(x') = \bar{\sigma}(x) + \lambda f, \; f \geq v = 246 GeV$$

Below breaking scale the symmetry is realized non-linearly

$$L \sim \sum_i g_i(\mu) O_i(x), \quad g_i(\mu) \to g_i(\mu\bar{\sigma}/f)(\bar{\sigma}/f)^{4-d_i}$$

Stage II (coupling of dilaton to **DP** sector in UV)

- **In UV:** $\frac{1}{M^{d_{UV}-2}} |\bar{\sigma}^2| O_{UV}, \quad \bar{\sigma}(x) = \sqrt{H^+ H}(x), \; m_\sigma^2 \sim x_\sigma f^2$

- **in IR** $\Downarrow$ flows to couplings of H to **DP** operator O_{IR}

$$const \frac{\Lambda^{d_{UV}-d_{IR}}}{M^{d_{UV}-2}} |H^2| O_{IR}$$

Scale invariance is almost breaking

DM particle is the only DP within the reach of the LHC energy

Kinetic term $\sim \varepsilon F_{\mu\nu} B^{\mu\nu}$ $\qquad SU_L(2)\times U_Y(1)\times U'_B(1) \Leftarrow$ **DP origin**

Triangle anomaly coupling $L_{S\gamma\bar{\gamma}} = \varepsilon\, g_{S\gamma\bar{\gamma}} F_{\mu\nu} B^{\mu\nu} S, \quad B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$

Basic object $S \to \gamma\bar{\gamma} \to \gamma\bar{\nu}\nu, \quad \boldsymbol{S} = \begin{cases} higgs \\ dilaton \end{cases}$

LO: $\sigma(pp \to SX) = \sigma^{exp}(pp \to HX) \times \dfrac{\Gamma^{th}(S \to gg)}{\Gamma^{SM}(H \to gg)}$

QCD radiative corrections $gg \to Higgs \overset{equal}{\Leftrightarrow} gg \to dilaton$

Increasing of $\sqrt{s} \Rightarrow$ Approx. conformal invariance $\dfrac{\partial g(\mu)}{\partial \mu} \cong 0$

Breaking @ $\sim f > v = \langle H \rangle_0$ by $\mu \approx M_{UV}\, \boldsymbol{exp}\left[-8\pi^2 / \left(b_0 g_0^2\right)\right]$

CA: $\partial_\mu K^\mu = \theta^\mu_\mu = \dfrac{\beta(g)}{2g} G^a_{\mu\nu} G^{\mu\nu a} + \sum_q m_q \left[1 + \gamma_m(g)\right] \bar{q}q \neq 0$

Why LHC13 instead of LHC7 ?

$S \sim m_S \sim f \sim s^{\alpha/2}$ Strong coupling theory.

At $\sqrt{s}$ below Λ, $\beta(g_i) \neq 0$ conformal breaking

$$L \sim \sum_i g_i(\mu) O_i(x), \quad \theta^\mu_\mu = \sum_i g_i(\mu)(d_i - 4) O_i(x) + \sum_i \beta_i(g) \frac{\partial}{\partial g_i} L$$

Scale invariance exact if $\beta(g_i) = 0$, $d_i = 4$

$$L_{trace} = \frac{\chi}{f} \theta^\mu_\mu(SM), \quad \theta^\mu_\mu \neq 0 \quad , \qquad \theta^\mu_\mu(SM) = \theta^\mu_\mu(SM)^{tree} + \theta^\mu_\mu(SM)^{anom}$$

Collider physics importance: $\theta^\mu_\mu(SM)^{anom} = -\frac{\alpha_s}{8\pi} b_o \sum G^a_{\mu\nu} G^{\mu\nu,a} - \frac{\alpha}{8\pi} b_{EM} F_{\mu\nu} F^{\mu\nu}$

Higgs has not such a coupling, only triangle-loop with heavy quarks

If QCD $\in$ Conformal sector: $\sum_{light} b_0 + \sum_{heavy} b_0 = 0 \quad \Rightarrow \quad b_0 = -11 + \frac{2}{3} n_{light}$ compared to Higgs

Important: The sum is splitting over all colored particles in mass scale separated by dilaton mass m_S

- Dilaton serves as the conformal compensator up to $f = v$.
- The σ contribution to $S \to \gamma\bar{\gamma}$ decays corresponds to including states lighter than σ.

Effect of DP sector on observable(s)

Mixing strength ε is bounded by $\varepsilon < \frac{s^d}{\left(v^2 M^{d-2}\right)^2}$

- Important: no dependence on $d_{UV},\ d_{IR},\ \Lambda$
- NP signals with DP increase with $\sqrt{s},\ d$

Assume $\varepsilon \sim O(3\%)$, DP visible @ LHC for $M < 10^3$ TeV, d=4

For $S \to \gamma\bar{\gamma}$: $L \sim O_{SM} O_{IR} \sim \varepsilon \bar{\psi} \gamma_\mu \psi \boldsymbol{S} B^\mu M^{-1}$

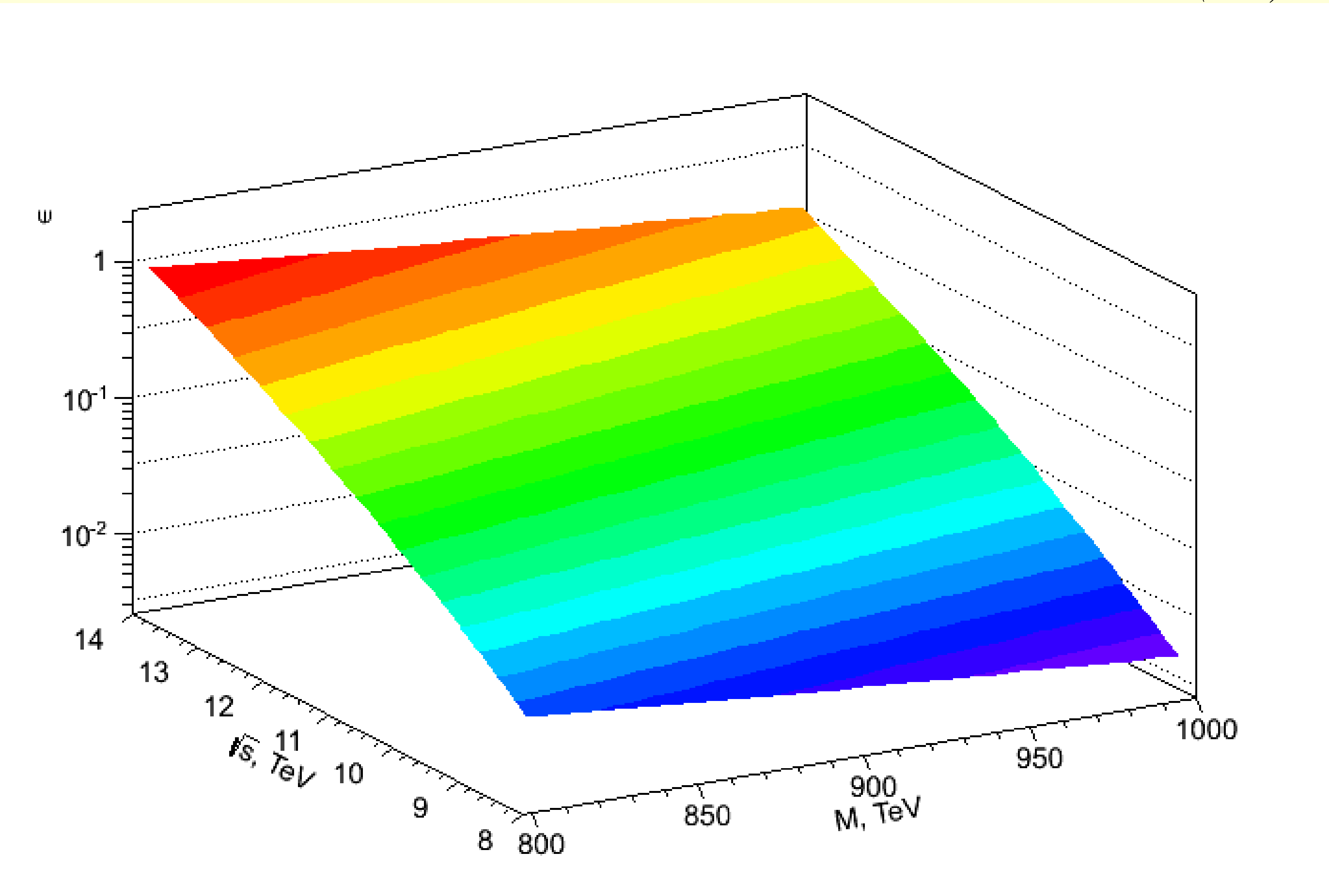
Relevant energy scale $Q \sim m_q,\ q : top, \ldots$

Result: $\varepsilon < 3 \cdot 10^{-2},\ q : top,\ d = 4; M > v$

LHC is a very good facility where the DM Physics can be tested well

Upper limit on $\varepsilon < \dfrac{s^d}{\left(v^2 M^{d-2}\right)^2}$, *LHC up to* $\sqrt{s} = 14\ TeV$, $M = 800 - 1000\ TeV$, $d = 4$

G.K., N.P. B273-275 (2016)



Estimation of DP mass m. *Upper limit*

$$Am\left(\bar{\gamma} \to \nu\bar{\nu}\right) = \frac{1}{2} f_{\nu}\bar{\nu}\left(g_{V_{\nu}}\gamma_{\beta} + g_{A_{\nu}}\gamma_{\beta}\gamma_{5}\right)\nu\bar{\gamma}_{\beta}$$

$$f_{\nu}^{2} = 4\sqrt{2}Gm^{2}, \quad G \sim 10^{-5} GeV^{-2}$$

No final state interactions: (partial decay width)

$$\Gamma\left(\bar{\gamma} \to \nu\bar{\nu}\right) = \frac{1}{3}\bar{\alpha}\cdot\varepsilon^{2} m,$$

$$\downarrow$$

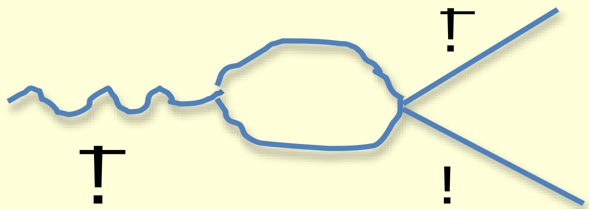
$$\frac{Gg_{\nu}^{2}m^{2}}{\sqrt{2\pi\bar{\alpha}}}, \quad g_{V_{\nu}}^{2} = g_{A_{\nu}}^{2} = g_{\nu}^{2} = \frac{1}{4}$$

For $\varepsilon < 3\cdot 10^{-2} \Rightarrow m < 3.3 GeV$

DP mass m in S ! " " ! "##

more detailed calculation are needed

E.g., EM ! F



$$! \left(" \# \; \nu\bar{\nu} \right) \sim \%^2 m^5 G^2 \left(ln \frac{\&_\nu^2}{m_l^2} ' \frac{1}{6} \right)^2$$

DP mass: Combined calculations give

$$m \,!\, m_{m} \left(\frac{3\sqrt{2}"}{' \# \sum_{l:e,m} \left(ln \frac{\Lambda_\%^2}{m_l^2} \& \frac{1}{6} \right)} \right)^{1/2} \; 4 \;\; 0.83\, GeV \,,\; \Lambda_\% \sim O\left(m_Z\right),\; e^+e^\& \& \; m^+m^\& loops$$

Mixing strength result $! = 7.6"10^{\#3}$

Agree with excl. region by BaBar (2015), E787+E949 (2014), as well as (g-2) (2014)

Model (Higgs-Dilaton Abelian gauge theory).

- TPWF, $\delta'\left(p^2, M^2\right)$ singularities/ $\sigma\left(x\right)$virtual state – dilaton

$A_\mu - B_\mu$ mixing $\qquad H - \bar{\sigma}$ LD

$$L_\varepsilon = -\frac{1}{2}\varepsilon F_{\mu\nu}B^{\mu\nu} - \xi\left(\partial A\right)\left(\partial B\right) + \bar{q}\left(i\hat{\partial} - m_q - g\hat{A}\right)q - I^\mu\left(B_\mu - \partial_\mu\sigma\right)$$

Gauge inv. $A_\mu \to A_\mu + \partial_\mu\alpha,\ B_\mu \to B_\mu + \partial_\mu\alpha,\ \sigma \to \sigma + \alpha,\ q \to qe^{ig\alpha},\ I_\mu \to I_\mu,\ \partial^2\alpha\left(x\right) = 0$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \xi = \varepsilon\bar{\xi}$$

Sub-canonical scalar operator $\sigma\left(x\right) = f^{-1}\bar{\sigma}\left(x\right)\begin{cases} \textit{primary operator} \\ \textit{grandfather potential} \end{cases}$

(primary means not a derivative of another operator)

$d \geq j_1 + j_2 + 2 - \delta_{j_1 j_2, 0}$ Dim. of the gauge inv. primary operator

$\sigma\left(x\right)$ provides the control over UV & IR divergences

LD & equations of motion

GK, arXiv:1604.04599 (2016)

$$L = L_\varepsilon + L_\sigma - \frac{1}{2} m^2 B_\mu^2 + L_{H\sigma}, \quad L_H \to L_\sigma = -\frac{\sigma}{\sqrt{2}} \sum_{q'} \left(m_{q'} + x_\sigma y_{q'} v \right) q' \bar{q}', \; x_\sigma = \frac{m_\sigma^2}{f^2} < 1$$

$$L_{H\sigma} = \frac{1}{2} \left[\left(\partial_\mu H \right)^2 + \left(\partial_\mu \bar{\sigma} \right)^2 \right] - \frac{\lambda}{4} \left(H^2 - \beta^2 \bar{\sigma}^2 \right)^2 - \frac{\eta}{4} \left(\bar{\sigma}^2 - f^2 \right)^2, \; \beta = \frac{\langle H \rangle}{\langle \bar{\sigma} \rangle} = \frac{v}{f}$$

$$\partial^2 B_\mu = \frac{1}{\varepsilon} Y_\mu + \left(1 - \bar{\xi} \right) \partial_\mu \partial^\nu B_\nu, \quad Y_\mu = g \bar{q} \gamma_\mu q \qquad (*)$$

$$B_\mu = \frac{\varepsilon}{m^2} \left[\partial^2 A_\mu - \frac{1}{\varepsilon} I_\mu - \left(1 - \bar{\xi} \right) \partial_\mu \partial^\nu A_\nu \right]$$

$$Eq. \, (*) + Eq. \, B_\mu(x) = \partial_\mu \sigma(x) \Rightarrow \qquad \left(\partial^2 \right)^2 \bar{\sigma}(x) \approx 0, \; f \neq 0$$

Dipole eq. for virtual field $\bar{\sigma}(x)$

What is the feature the dilaton field is characterized by?

TPWF (two-point Wightman function) $\left(!\,^{2}\right)^{2}{}'' \left(x\right) = 0 \;\#\; \left(!\,^{2}\right)^{2} \bar{\sigma}\left(x\right) = 0$

General solution (expansion),

$! \left(x\right)'' \; S\#\!\left(R^{4}\right)$ of temperate generalized functions on R^{4}

$$! \left(x\right) = b_1\, ln \frac{l^{2}}{''\, x_{\mathrm{m}}^{2} + i\#x^{0}} + b_2 \frac{1}{x_{\mathrm{m}}^{2}\, ''\, i\#x^{0}} + b_3$$

- ✓ parameter l breaks the scale invariance.

(Dilatation properties: $!\left(''x\right) = !\left(x\right)\# \frac{1}{\left(8\pi\right)^{2}} ln\, ''\,, \quad '' > 0$)

- Allow: est. the propagator of $!\left(x\right) \;\; !$ propagator of DP

Commutators

$$\left[\Gamma(x),\Gamma(0)\right] = 2\&i\ \ sign\left(x^0\right)\left\{b_1'\left(x^2\right) + b_2(\left(x^2\right)\right\}$$

- Coefficients $\quad b_1 \ ! \quad CCR \quad \left[A_m(x), " A_\#(0)\right]_{x^0=0} = ig_{m\#}(^3(\vec{x}))$

$\quad b_2 \ ! \quad CCR \quad \left[\Gamma(x), \#_\Gamma(0)\right]_{x^0=0} = i(^3(\vec{x}))$

➢ To fix both b_1 and b_2 we choose:

$$I_m \ ! \quad I_m = "m^2\left(\#_m\sigma \% A_m\right)$$

(invariant under gauge transformations)

- LD mixing term $\ ! m^2\left(A_m " \#_m\sigma\right)\left(B_m " \#_m\sigma\right)$ *addit.* to $\sim ! F_{m\prime} B^{m\prime}$

Stueckelberg-like term

Propagator of Dark Photon

- $□_{m''}(p) = p_m p_{''}\, □(p), \quad □(p) \sim \frac{''}{\#}\left[□_1(p) + □_2(p)\right]$

$$□_1(p) = \frac{1}{''(1+\#)} \lim_{\lambda^2 \% 0} \left[\frac{1}{(p^2 \& \lambda^2 + i\#)^2} + i'^{\,2} \ln(l^2\lambda^2)\,(_4(p) \right]$$ *mixing part*

$$□_2(p) = '' \frac{1}{2(f^2 '' m^2)} \frac{1}{p^2 + i\#}$$ *conformal breaking part*

- ✓ The strong gauge condition $B_m(x) = !_m{}^{''}(x)$ used
- ○ In case no mixing, $□_{m''}(p)\#$ standard photon propagator
- ➢ Dilaton mass does not enter the final solution

Conclusion

1. Influence of Conformal Sector (DP) to SM particle sector;
2. Upper limit for mixing strength $! < 3''10^{\#2}$

3. Interaction between DP & quarks is mediated by $!_m''$;
4. Dilaton is a portal to DP propagation with $!^2\left('' \# B\right) = 0$
5. DP solutions, DP massive, $m = 0.83\ GeV$, $!$ $! = 7.6''10^{-3}$

6. Dilaton mass does not enter the final solution.
7. If $! = 0$, $S''\ \#\# \Rightarrow H''\ \#\#$
8. LHC13: decay $S\,!\ ''\!''$ is evident through *a single photon* plus $E\!\!\!/_T$ signature, with both energies peaked at $0.5m_s$

! LHC: !! channel in scalar decay is the best probe to discover DP